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Observations in the THz Gap: The Josephson-Plasma Resonance of $Bi_2Sr_2CaCu_2O_8$

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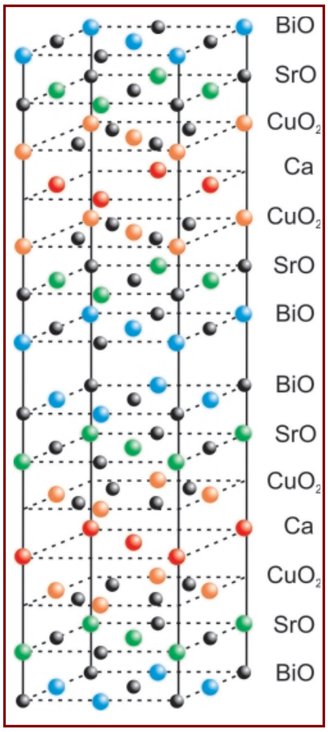

Fig. 1 : Multilayered structure of $Bi_2Sr_2CaCu_2O_8$

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Superconductivity is a phenomenon of matter where below a defined temperature (T_c) the electrical resistance drops dramatically and the specific resistance is zero. Therefore, electric currents can propagate for many years without energy loss. "Classical" superconductors, with T_c between 4 - 23 K, require liquid helium for cooling which is not feasible for many technological applications. High-temperature superconductors with T_c of around 100 K would be far more suitable since liquid nitrogen can be used for cooling. However, the production of these compounds for technological applications is still unsolved since they are ceramic oxides which cannot be manufactured like metal wires.

Most high temperature superconductors are multilayer structures of metal oxides, like the cuprite $Bi_2Sr_2CaCu_2O_8$ (Fig.1). This compound consists of CuO_2 layers which are separated by insulating layers of Bi- and Sr-oxide or Ca. The assembly of conducting-insulating-conducting layers is termed as Josephson-junction. In the normal state (beyond T_c) $Bi_2Sr_2CaCu_2O_8$ behaves like a quasi 2-dimensional metal and electric current flows only along the CuO_2-layers. Below T_c these materials become 3-dimensional superconductors. Electric current flows perpendicular to the CuO_2 layers propagated by pairs of electrons (Cooper-pairs) which are tunneling the insulating interlayers. The entity of Cooper-pairs form an electron gas (Josephson-plasma) which can be described by a wave function with a specific frequency. For bilayer compounds (and hence two different Josephson-junctions) this results in two kinds of plasma frequencies. Their out-of phase oscillation gives rise to the so called Josephson-plasma resonance which has been assigned to the absorption peak that develops blow T_c.

The electronic properties perpendicular to the CuO_2 planes cover a broad spectrum, from marginally conducting overdoped $YBa_2Cu_3O_7$, to the essentially insulating character of $Bi_2Sr_2CaCu_2O_8$. The role of this varying degree of anisotropy in the CuO_2 intralayer and interlayer electronic properties in producing high temperature superconductivity is still unresolved [1]. Characterization of the Josephson-plasma resonance is of particular importance for the understanding the role of anisotropy and thus of high temperature superconductivity.

The energy scale of the Josephson-plasma edge is related to the degree of anisotropy of the material. In nearly all families of high temperature superconductors the plasma edge has been observed in the far infrared frequency range [2]. One exception is in the extremely anisotropic $Bi_2Sr_2CaCu_2O_8$ (Fig. 1) where at optimal doping (maximum T_c) the plasma edge has not been seen. By doping this compound with lead, and hence lowering the anisotropy (and T_c), the plasma edge is observed near 40 cm^{-1} [3]. Additionally, when reducing the carrier doping a resonance is observed in magneto-absorption experiments in the microwave region, usually attributed to the Josephson-plasma effect [4].

The energy range between microwave and far infrared, 3 – 33 cm^{-1} (0.1 – 1 THz), has proven to be challenging to access and is therefore referred to as the 'THz gap'. Using the stable coherent synchrotron radiation (CSR) recently provided at BESSY [5] (see page 49) we have been able to extend

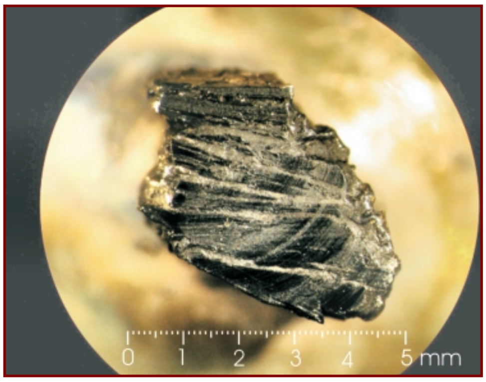

Fig. 2: The mosaic of the single $Bi_2Sr_2CaCu_2O_8$ crystals used in this investigation. To account the contribution to the measured reflectance the area of epoxy showing was estimated and the experimental reflectance was corrected accordingly.

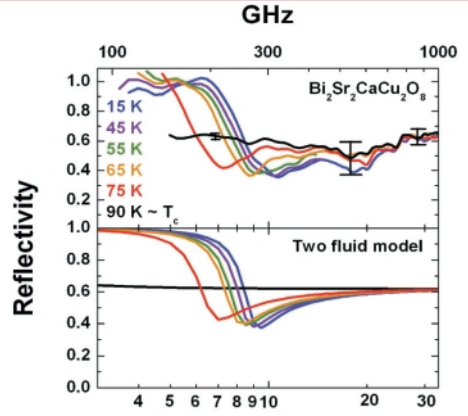

Fig. 3:
Measured c-axis polarized near-normal reflectivity of $Bi_2Sr_2CaCu_2O_8$ (upper panel) for various temperatures at or below the superconducting transition temperature, T_c. A resonance that shifts with temperature and disappears above T_c is clearly observed. The lower panel shows the calculated reflectivity of a superconductor with a shifting Josephson-plasma resonance.

traditional infrared measurements into sub-terahertz frequency range. Reflectivity measurements on optimally doped $Bi_2Sr_2CaCu_2O_8$ to 4 cm^{-1} show the Josephson-plasma resonance in the expected region.

In order to make specular reflectance measurements at wavelengths in excess of 1 mm it is necessary to have a sample larger than the wavelength of the probing radiation. Since it is difficult produce a single crystal of high temperature superconductors with c-axis dimension longer than 1 mm, a mosaic of several crystals was assembled with a net c-axis length of approx. 5 mm (Fig. 2). While this circumvents problems of diffraction effects, additional complications arise due to reflection from the conducting epoxy that binds the individual crystals together. Absolute values of the reflectivity were obtained by coating the sample in situ with a thin layer of gold and using the gold coated sample as a reference.

The top panel of Figure 3 shows the experimental reflectance in the sub-terahertz region on a logarithmic frequency scale. In contrast to the nearly flat and featureless spectrum at $T = T_c$ (black curve), the $R(\omega)$ spectra at $T < T_c$ shows a strong ω dependence. Below T_c the spectrum has a shallow minimum followed by a strong rise in the reflectivity. This reflectance edge and the minimum mark the onset of superconducting currents along the c-axis. Their position may be used to measure the superfluid density: As the temperature decreases in the superconducting state, both the minimum and reflectance edge shifs to higher frequencies. This shift nearly saturates at 15 K due to the increasing density of superfluid as the temperature is lowered.

In order to extract quantitative information from the spectrum we model the reflectance with a two fluid model. One component consists of the dissipationless supercurrents, while the other is an over damped plasmon. The second term is necessary to account for finite reflectivity at the plasma minimum and the rounding at the top of the reflectance edge. The bottom panel of Figure 3 shows the results of this modeling. The magnitude and both the frequency and temperature dependence of the data in the top panel are well accounted for.

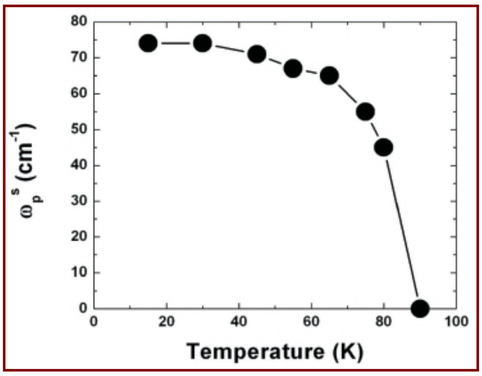

Fig. 4:
Superfluid plasma frequency as a function of temperature. Plasma frequency was determined from fitting the reflectance spectra with the two fluid model shown in the bottom panel of Fig. 3.

Using the above modeling we are able to extract the value of the unscreened Josephson plasma frequency. At 15 K we obtain a value of ω_{ps} = 74 cm^{-1}. This value corresponds to a c-axis penetration depth value of λ_c = 21 µm. The complete temperature dependence of the Josephson-plasma frequency is summarized in Fig. 4. The plasma frequency rises quickly below T_c, and is nearly saturated at the low temperature limit by $T_c/2$.

Another dip in our experimental data near 20 cm^{-1} might be a transverse Josephson-plasma mode [6] in $Bi_2Sr_2CaCu_2O_8$ caused by the two different distances between CuO_2 layers in the crystal structure. This feature in the data is however located right where our signal to noise is the worst due to interference from 50 Hz pickups, so for now this remains only a tantalizing prospect and should be investigated further.

The production of stable, high power, coherent synchrotron radiation at sub-terahertz frequency opens a new region in the electromagnetic spectrum to explore physical properties of materials. Just as conventional synchrotron radiation has been a boon to X-ray science, coherent synchrotron radiation may lead to many new innovations and discoveries in terahertz physics. As an initial feasibility test of using CSR in scientific applications, we have directly measured the Josephson plasma resonance in optimally doped $Bi_2Sr_2CaCu_2O_8$ for the first time. Our results provide a connection between the magneto-absorption experiments performed on underdoped $Bi_2Sr_2CaCu_2O_8$ and the infrared experiments in other families of high temperature superconductors.

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